IEEE 802.15.7 Visible Light Communication: Modulation Schemes and Dimming Support

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ABSTRACT

Visible light communication refers to short-range optical wireless communication using visible light spectrum from 380 to 780 nm. Enabled by recent advances in LED technology, IEEE 802.15.7 supports high-data-rate visible light communication up to 96 Mb/s by fast modulation of optical light sources which may be dimmed during their operation. IEEE 802.15.7 provides dimming adaptable mechanisms for flicker-free high-data-rate visible light communication.

INTRODUCTION

Visible light communication (VLC) refers to short-range optical wireless communication using the visible light spectrum from 380 to 780 nm. VLC transmits data by intensity modulating optical sources, such as light emitting diodes (LEDs) and laser diodes, faster than the persistence of the human eye [1–3]. There has been renewed interest in visible light optical communication due to the widespread deployment of LEDs for energy efficiency and recent advancements in LED technology with fast nanosecond switching times. Traditional radio frequency (RF) communication below 6 GHz is rapidly running out of spectrum bandwidth for high-data-rate communication. With ~300 THz of bandwidth available for VLC, multi-gigabit-per-second data rates could be provided over short distances, for example, using arrays of LEDs in a multiple-input multiple-output (MIMO) fashion [4]. In addition, communication is provided in conjunction with lighting providing gigabit-per-second data rates with only simple LEDs and photodetectors (PDs) compared to expensive RF solutions that require high power consumption (Watts) for transmitting, sampling, and processing gigabit-per-second data.

The two main challenges for communication using visible light spectrum are flicker mitigation and dimming support. Flicker refers to the fluctuation of the brightness of light. Any potential flicker resulting from modulating the light sources for communication must be mitigated because flicker can cause noticeable, negative/harmful physiological changes in humans. To avoid flicker, the changes in brightness must fall within the maximum flickering time period (MFTP). The MFTP is defined as the maximum time period over which the light intensity can change without the human eye perceiving it. While there is no widely accepted optimal flicker frequency number, a frequency greater than 200 Hz (MFTP < 5 ms) is generally considered safe [5]. Therefore, the modulation process in VLC must not introduce any noticeable flicker either during the data frame or between data frames. Dimming support is another important consideration for VLC for power savings and energy efficiency. It is desirable to maintain communication while a user arbitrarily dims the light source. The human eye responds to low light levels by enlarging the pupil, which allows more light to enter the eye. This response results in a difference between perceived and measured levels of light. The relation between perceived and measured light is given by [6]

$$\text{Perceived light}(\%) = 100 \times \sqrt{\frac{\text{Measured light}(\%)}{100}} \tag{1}$$

As shown in Fig. 1, a lamp that is dimmed to 10 percent of its measured light output is perceived as being dimmed to only 32 percent. Hence, communication support needs to be provided when the light source is dimmed over a large range, typically between 0.1–100 percent.

VLC is being investigated by a number of universities, corporations, and organizations worldwide. In 2007 the Japan Electronics and Information Technology Industries Association's (JEITA) established standards for a "visible light ID system." In 2008, the Visible Light Communications Consortium (VLCC) introduced a Specification Standard. The Home Gigabit Access project (OMEGA) in Europe is also developing VLC for home networks [3]. Howev-

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er, none of the above standards focus on flicker mitigation and dimming, which has been integrated into IEEE 802.15.7 and is the focus of this article. The IEEE 802.15.7 standard supports multiple diverse topologies, such as peer-to-peer and star topologies, with data rates ranging from 11.67 kb/s to 96 Mb/s for indoor and outdoor applications. In the following sections, the article describes the various modulation methods available in IEEE 802.15.7 and their benefits for flicker mitigation and dimming.

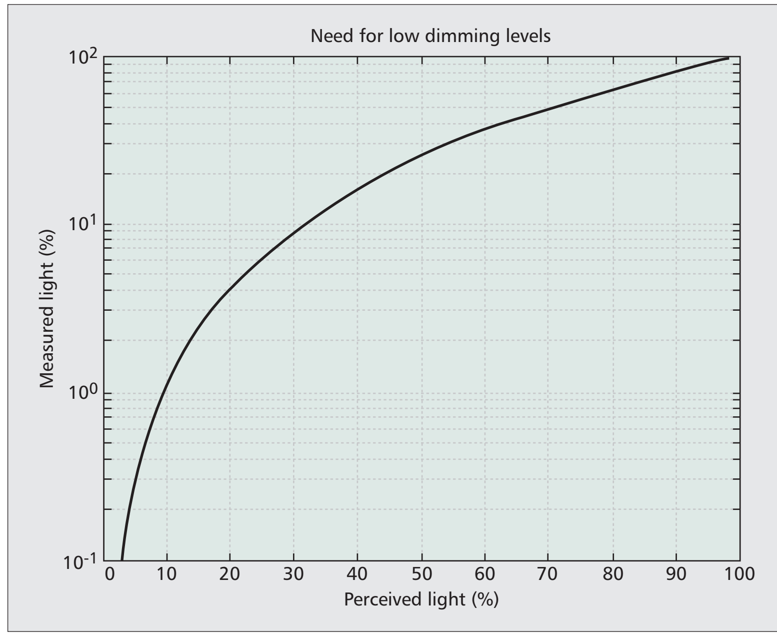

Figure 1. *Human eye shows nonlinear sensitivity to dimming [6], motivating the need for high-resolution dimming support.*

Modulation Methods Incorporated in 802.15.7

The IEEE 802.15.7 standard offers three physical (PHY) types for VLC. PHY I operates from 11.67 to 266.6 kb/s, PHY II operates from 1.25 to 96 Mb/s and PHY III operates between 12 and 96 Mb/s. PHY I and PHY II are defined for a single light source, and support on-off keying (OOK) and variable pulse-position modulation (VPPM). PHY III uses multiple optical sources with different frequencies (colors) and uses a particular modulation format called color shift keying (CSK). The different modulation schemes allow trade-offs between data rates and different dimming ranges [7]. For example, under dimming conditions, modulation using OOK provides constant range and variable data rate by inserting compensation time, while modulation using VPPM provides constant data rate and variable range by adjusting the pulse width. All three PHYs have been crafted to coexist with each other while mitigating flicker and supporting dimming.

Each PHY mode contains mechanisms for modulating the light source, run length limited (RLL) line coding, and channel coding for forward error correction (FEC). RLL line codes are used to avoid long runs of 1s and 0s that could potentially cause flicker and clock and data recovery (CDR) detection problems. RLL line codes take in random data symbols at input and guarantee DC balance with equal 1s and 0s at the output for every symbol. Various RLL line codes such as Manchester, 4B6B, and 8B10B are defined in the standard, and provide trade-offs between coding overhead and ease of implementation. IEEE 802.15.7 also supports various FEC schemes to work reasonably well in the presence of hard decisions that would be generated by the CDR. The channel codes support both long and short data frames for high-data-rate indoor and low-data-rate outdoor applications. For outdoor applications, stronger codes using concatenated RS and CC codes are developed to overcome the additional path loss due to longer distance and potential interference introduced by optical noise sources such as daylight and fluorescent lighting. Reed-Solomon (RS) and convolutional codes (CC) are preferred over advanced coding schemes such as low density parity check (LDPC) codes in order to support short data frames, hard decision decoding, low complexity, and their ability to interface well with RLL line codes. For indoor applications, where the coding requirements are less stringent for short distances, RS codes are used for FEC since they are better suited to high-data-rate implementations. RS codes also interface well in conjunction with the RLL line codes, where the errors detected from the RLL line code at the receiver could be marked as erasures to the RS decoder, providing performance improvements of around 1 dB. For PHY I, an interleaver between the RS code and the CC code provides an additional 1 dB of performance improvement.

Each PHY modulation mode has an associated optical clock rate which is "divided down" by the various coding schemes to obtain the final resulting data rates, as shown in Tables 1, 2, and 3. The optical clock rate for PHY I is chosen to be ≤ 400 kHz to account for the fact that LEDs used in applications such as traffic lights require high currents to drive the LEDs and therefore switch slowly. For PHY II, the optical clock rate is chosen to be ≤ 120 MHz to accommodate fast LEDs used in mobile and portable devices for communication. The optical clock rate is chosen to be ≤ 24 MHz, which is the maximum clock rate supported by current infrastructure (white) LEDs used in PHY III. The standard also supports the use of different clock rates with the same device for transmitting and receiving data since the transmitter (LED) and receiver (PD) are independent circuits. The infrastructure could be transmitting at a lower clock rate using slower but brighter LEDs while receiving at a higher clock rate from a portable device that has faster but weaker LEDs.

OOK Modulation and Dimming Method

OOK modulation is the simplest modulation scheme for VLC, where the LEDs are turned on or off dependent on the data bits being 1 or 0. While the modulation is logically OOK, OOK "off" does not necessarily mean the light is completely turned off; rather, the intensity of the light may simply be reduced as long as one can

Modulation	RLL code	Optical clock rate	FEC		Data rate
			Outer code (RS)	Inner code (CC)	
OOK	Manchester	200 kHz	(15,7)	1/4	11.67 kb/s
			(15,11)	1/3	24.44 kb/s
			(15,11)	2/3	48.89 kb/s
			(15,11)	None	73.3 kb/s
			None	None	100 kb/s
VPPM	4B6B	400 kHz	(15,2)	None	35.56 kb/s
			(15,4)	None	71.11 kb/s
			(15,7)	None	124.4 kb/s
			None	None	266.6 kb/s

Table 1. *PHY I operating modes.*

distinguish clearly between the "on" and "off" levels. The OOK mode transmitter block diagram in Fig. 2 shows the bits from the upper layers entering the FEC before being Manchester RLL coded. The Manchester encoding embeds the clock into the data by representing a logic zero as an OOK symbol "01" and a logic one as an OOK symbol "10," providing a DC balanced code.

Modulation	RLL code	Optical clock rate	FEC	Data rate
VPPM	4B6B	3.75 MHz	RS(64,32)	1.25 Mb/s
			RS(160,128)	2 Mb/s
		7.5 MHz	RS(64,32)	2.5 Mb/s
			RS(160,128)	4 Mb/s
			None	5 Mb/s
OOK	8B10B	15 MHz	RS(64,32)	6 Mb/s
			RS(160,128)	9.6 Mb/s
		30 MHz	RS(64,32)	12 Mb/s
			RS(160,128)	19.2 Mb/s
		60 MHz	RS(64,32)	24 Mb/s
			RS(160,128)	38.4 Mb/s
		120 MHz	RS(64,32)	48 Mb/s
			RS(160,128)	76.8 Mb/s
			None	96 Mb/s

Table 2. *PHY II operating modes.*

OOK dimming can be achieved by either redefining the "on" or "off" levels of the OOK symbol to have a lower intensity, or the levels can remain the same and the average duty cycle of the waveform can be changed by the insertion of "compensation" time into the modulation waveform. The compensation time is realized by fully turning on or off the light source for the required duration to provide dimming. This allows a DC component, which determines the light intensity, to be added to the waveform controlling the light source. For example, if the brightness of data is A percent with period T_1 and the compensation symbols have an average brightness B percent with period T_2, the resulting average brightness N (percent) can be given by

$$N = \frac{AT_1 + BT_2}{T_1 + T_2} \tag{2}$$

The two methods impact performance in different ways. The first method, redefining the "on" and "off" levels of OOK, gives a constant bit rate as the light dims, which means the range must decrease, but it also risks color shift due to the LEDs being underdriven. On the other hand, the insertion of compensation time results in a lower bit rate as the light dims, which implies a reduced bit rate with constant range. However, there has also been related work using compression techniques to reduce the bit rate reduction [8].

The OOK dimming frame's structure is shown in Fig. 3. The frame structure consists of a preamble for synchronization, a PHY header that provides details on the frame such as the frame length, modulation, and coding, and the data payload frame. When compensation time is added, it is possible for the receiver to lose synchronization for long compensation times, since the clock at the receiver is typically recovered from the data. Hence, in the OOK dimming frame structure, the data frame is broken into subframes, and each subframe can be preceded by a resynchronization (resync) field using a 1010… maximum transition sequence pattern that aids in readjusting the data clock after the compensation time. The data frame is fragmented into subframes of the appropriate length after the FCS has been calculated and the FEC applied. An example of OOK dimming to increase brightness by adding compensation symbols is shown in Fig. 4. The average brightness (AB) of *N* percent is achieved by adjusting the brightness of the data and the compensation symbols. When OOK modulation is used for data communication, the data inherently has a 50 percent duty cycle due to Manchester RLL coding. In order to adjust the duty cycle within the frame, the compensation symbols of the appropriate duration and brightness (as defined in Eq. 2) need to be applied to maintain the AB of *N* percent. Outside the data communication frame, idle patterns of *N* percent average brightness are sent to ensure the net average brightness from the illumination source remains consistent.

VPPM Modulation and Dimming Method

The use of modulation techniques such as pulse position modulation (PPM) for dimming support has been proposed for VLC [7]. Variable pulse-position modulation (VPPM) changes the duty cycle of each optical symbol to encode bits. The variable term in VPPM represents the change in the duty cycle (pulse width) in response to the requested dimming level. VPPM optical symbols are distinguished by the pulse position. As shown in Fig. 5a, VPPM is similar to 2-PPM when the duty cycle is 50 percent. The logic 0 and logic 1 symbols are pulse width modulated depending on the dimming duty cycle requirement. As shown in Fig. 5b, the pulse width ratio (*b*/*a*) of PPM can be adjusted to produce the required duty cycle for supporting dimming by pulse width modulation (PWM). Figure 6 shows an example waveform of how VPPM can attain a 75 percent dimming duty cycle requirement, where both logic 0 and logic 1 have a 75 percent pulse width.

The VPPM mode transmitter block diagram is shown in Fig. 7. The input is sent through an RS FEC encoder for error protection, followed by a 4B6B RLL code for DC balance and flicker mitigation. The 4B6B coding takes a random 4-bit symbol and changes it into a DC balanced 6-bit code as shown in Table 4. The counts of 1 and 0 in every VPPM encoded symbol are always equal to 3. Since the bit rate is constant regardless of the requested dimming level, as the light is dimmed, the range decreases with the dimming level. The features of the 4B6B RLL code are:

- Always 50 percent duty cycle during one encoded symbol
- DC balanced run length limiting code
- Error detection capability
- Run length limited to four
- Reasonable clock recovery

Figure 8 shows how the light intensity for the payload can be adjusted by adapting the pulse width of VPPM symbols. The light intensity for the preamble and header can be adjusted by inserting compensation symbols of the appropriate length and intensity before the frame. The AB of *N* percent is achieved by adjusting the brightness of the data and the compensation symbols. When VPPM modulation is used for data communication, the data inherently have the required duty cycle and hence, the requirement for compensation time within the data frame is mitigated. However, the preamble and header are always at 50 percent duty cycle, since they are not aware of the VPPM modulation. Therefore, some adjustment in compensation time may be required to keep the average brightness of N percent consistent. However, it may be difficult to achieve arbitrary duty cycles using VPPM to support large dimming ranges. Hence, the VPPM symbols also time-multiplex with different dimming levels within the frame in order to attain high resolution up to 0.1 percent. This is discussed in detail later.

CSK Modulation and Dimming Method

White LED lights are generated by using a mixture of different colors in typically two different methods. White LEDs can be generated using

Modulation	Optical clock rate	FEC	Data rate
4-CSK	12 MHz	RS(64,32)	12 Mb/s
8-CSK		RS(64,32)	18 Mb/s
4-CSK	24 MHz	RS(64,32)	24 Mb/s
8-CSK		RS(64,32)	36 Mb/s
16-CSK		RS(64,32)	48 Mb/s
8-CSK		None	72 Mb/s
16-CSK		None	96 Mb/s

Table 3. *PHY III operating modes.*

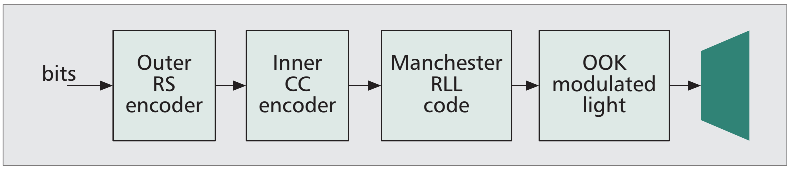

Figure 2. *OOK transmitter block diagram. The figure shows the bits sent from the upper layers being encoded for error protection and to provide DC balance.*

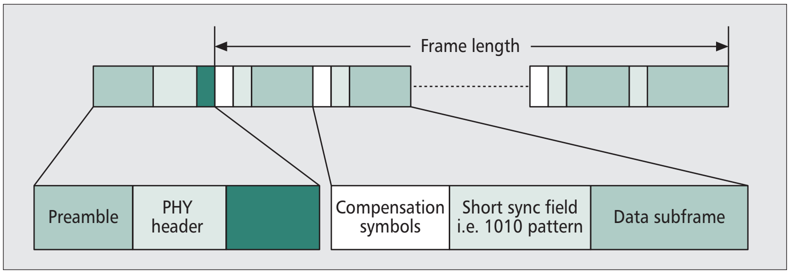

Figure 3. *OOK dimming structure. The figure shows the frame structure for OOK dimming, where compensation symbols are added in time to maintain the desired visibility level, and short sync fields are used to resync the receiver before the data subframes.*

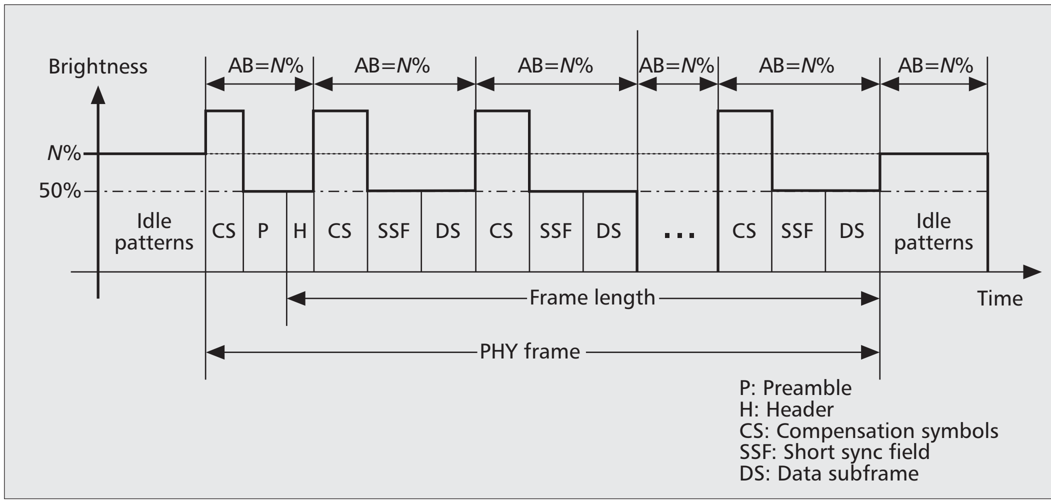

Figure 4. *Dimming support using OOK modulation. The figure shows the use of idle patterns (when there is no data) and the use of compensation symbols (in the presence of data using OOK) to maintain an average brightness (AB) of N percent.*

blue LEDs with yellow phosphor. However, yellow phosphor slows down the switching response of the white LEDs. Alternately, faster white LEDs that can be more useful for communication can be generated by simultaneously exciting red, green and blue LEDs [9, 10]. The use of such multi-color LEDs forms the principle behind CSK modulation. Color shift keying modulation is similar to frequency shift keying in that the bit patterns are encoded to color (wavelength) combinations. For example, for 4-CSK (two bits per symbol) the light source is wavelength keyed such that one of four possible wavelengths (colors) is transmitted per bit pair combination. In order to define various colors for communication, the IEEE 802.15.7 standard breaks the spectrum into 7 color bands in order to provide support for multiple LED color choices for communication. Figure 9 shows the center of the seven color bands on xy color coordinates as defined by CIE 1931 color coordinates [11]. The 3-bit values in Fig. 9 represent each of the seven color bands. The CSK signal is generated by using three color light sources out of the seven color bands. The three vertices of the CSK constellation triangle are decided by the center wavelength of the three color bands on xy color coordinates. CSK has the following advantages:

• The final output color (e.g., white) is guaranteed by the color coordinates shown in Fig. 9: CSK channels are determined by mixed colors that are allocated in the color coordinates plane.

• The total power of all CSK light sources is constant, although each light source may have a different instantaneous output power. CSK dimming ensures that the average optical power

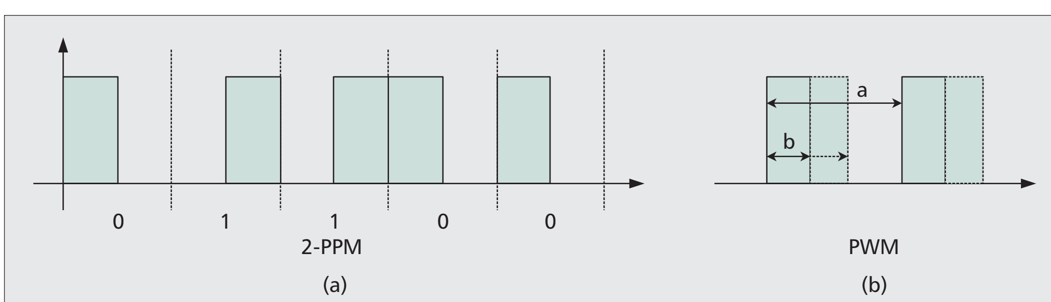

Figure 5. *Basic concept of VPPM. VPPM is similar to 2-PPM, as shown in a) for 50 percent visibility, and the duty cycle is adapted using PWM for other visibility levels as shown in b).*

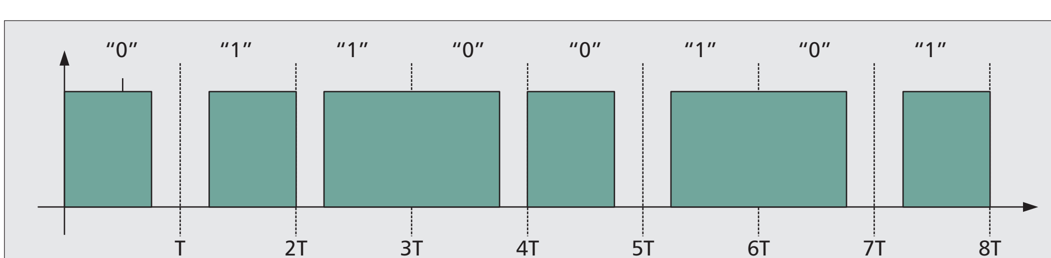

Figure 6. *Waveform of VPPM signal with 75 percent pulse width.*

from the light sources is kept constant and maintains the requisite intensity of the center color of the color constellation. Thus, there is no flicker issue associated with CSK due to amplitude variations. CSK dimming employs amplitude dimming and controls the brightness by changing the current driving the light source. However, care needs to be observed during CSK dimming to avoid unexpected color shift in the light source.

• CSK supports amplitude changes with digital-to-analog (D/A) converters (higher complexity), thus allowing higher order modulation support to provide higher data rates at a lower optical clock frequency. PHY I and PHY II allow only OOK modulation, thereby limiting their data rate to 1 b/clock.

The communication using CSK modulation with 4-CSK symbol points, for example, are defined by the design rule in Fig. 10. Points *I*, *J* and *K* show the center of the three color bands on *xy* color coordinates. *S0* to *S3* are four symbol points of 4-CSK. *S1*, *S2*, and *S3* are three vertices of the triangle IJK. *S0* is the centroid of the triangle *IJK*. The absolute values for 4-CSK for multiple combinations of the optical sources, assuming the spectral peak of the optical source is at the center of the band plan, can be obtained in [12].

Figure 11 shows the CSK system configuration for PHY III with three color (bands *i*, *j* and *k*) light sources. After scrambling and channel coding, the logical data values (zeros and ones) are transformed into *xy* values, according to a mapping rule on the *xy* color coordinates by the color coding block. The scrambler is necessary to create pseudo-random data and prevent data-pattern-dependent color shifts. The data parts of the frame are subject to the FEC block for error protection. These *xy* values are transformed into intensity P_i, P_j and P_k. The relation between the coordinates and the intensity is shown in Eqs. 3–5. On the receiver side, *xy* values are calculated from the received light powers of 3 colors, and *xy* values are decoded into the received data.

$$x_p = P_i x_i + P_j x_j + P_k x_k \quad (3)$$

$$y_p = P_i y_i + P_j y_j + P_k y_k \quad (4)$$

$$P_i + P_j + P_k = 1 \quad (5)$$

Dimming Mechanisms for Flicker-Free Communication

This section outlines the system design for dimming support that is enabled by the modulation methods and physical layer support discussed in the previous section.

Idle Pattern Dimming

An idle pattern is defined as a pattern whose duty cycle variation results in a change of brightness to support dimming and may be transmitted during idle or receive mode. An idle pattern can be transmitted during medium access layer (MAC) idle (no data transmission) or receive (RX) operation states for infrastructure light sources. This helps maintain visibility and flicker-free operation. The data and the idle pattern should have the same duty cycle to minimize flicker. This idle pattern, and its dependence on the dimmer setting, is shown in Fig. 12. The transition between active communication and idle operation occurs on a large timescale (block active/idle/RX). However, within an active communication session, there can be small timescale transition between active, idle, and RX modes. The final output from the light source should show a constant duty cycle irrespective of the MAC state of the device. Dimmer setting (a) illustrates a higher switching frequency for higher brightness, while dimmer setting (b) illustrates a lower switching frequency for lower brightness.

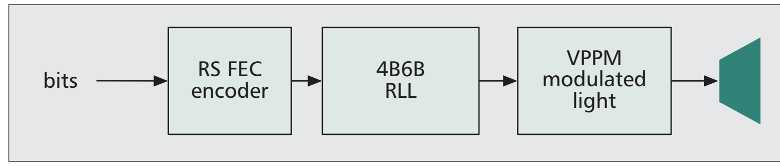

Figure 7. *VPPM transmitter block diagram. The figure shows the bits sent from the upper layers being encoded for error protection and to provide DC balance.*

4B (input)	6B (output)	Hex
0000	001110	0
0001	001101	1
0010	010011	2
0011	010110	3
0100	010101	4
0101	100011	5
0110	100110	6
0111	100101	7
1000	011001	8
1001	011010	9
1010	011100	A
1011	110001	B
1100	110010	C
1101	101001	D
1110	101010	E
1111	101100	F

Table 4. *Mapping input 4B to output 6B.*

Hybrid Idle Pattern and Compensation Time Dimming

The idle pattern mechanism allows an idle pattern to be inserted between the data frames for light dimming, as shown in Fig. 13. The duty cycle of the idle pattern can be adjusted to vary

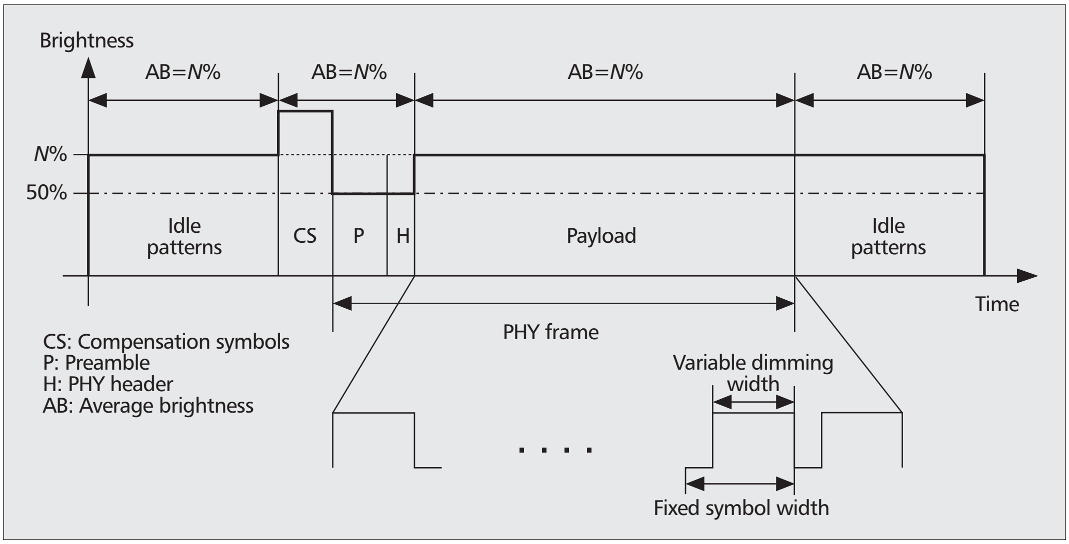

Figure 8. *Frame structure to meet dimming requirements using VPPM. When VPPM is used for the data, the visibility level for dimming is automatically satisfied. However, since the preamble and header is encoded using OOK, compensation symbols can be used to accommodate the difference in brightness during the preamble and header.*

the brightness. An idle pattern can either be in-band or out-of-band as defined by the modulation domain spectrum shown in Fig. 14 (i.e., the spectrum observed at the output of the PD). Both types of idle patterns are supported. Figure 14 shows the modulation spectrum divided into three regions: flicker, out-of-band, and in-band. The flicker region is defined from DC to < 200 Hz where eye safety may be of concern. Ambient light interference (50-60 Hz) also falls in this region. Hence, this region should be avoided for communication. The region between the flicker and in-band modulation is defined as out-of-band. An out-of-band region is needed for multiple PHYs to coexist. For example, PHY I can lie in the out-of-band region of PHY II since it supports a lower data rate. An in-band idle pattern does not require any change in the clock and can be seen by the receiver. An out-of-band idle pattern is typically sent at a much lower optical clock rate (including the option of maintaining visibility via a DC bias only) and is not seen by the receiver (i.e., is not in the receiver modulation domain bandpass). The compensation time is defined as the idle time inserted in the idle pattern or in the data frame where the light is turned on and off with the appropriate ratio to meet dimming duty cycle requirements.

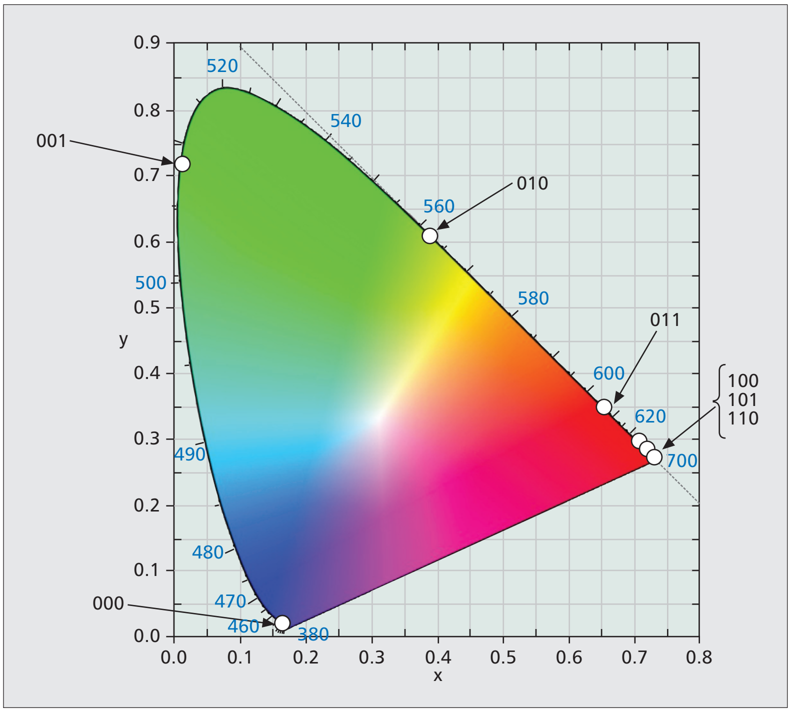

Figure 9. *CIE 1931 xy color coordinates [11], where x and y are the chromaticity values. The outer curve is the spectral locus with wavelengths shown in nm. The three-digit values refer to the center wavelength of the seven bands defined in the IEEE 802.15.7 band plan.*

Visibility Pattern Dimming

To support continuous illumination from infrastructures, the standard provides support for frames that do not contain any data but send only idle patterns to maintain continuous visibility support. Visibility pattern dimming is similar to idle pattern dimming except that the patterns are used inside the payload of a visibility frame. However, these visibility patterns need to support the high resolution required for dimming of 0.1 percent discussed earlier. The visibility patterns support features such as flicker mitigation, continuous visibility, device discovery and color stabilization. The visibility patterns are not encoded in the PHY layer and do not have a frame check sequence (FCS) associated with them. To generate high resolution visibility patterns from 0 to 100 percent in steps of 0.1 percent, certain constraints must be considered in designing the visibility patterns.

- The number of transitions between 0s and 1s can be maximized to provide high-frequency switching to avoid flicker and help the CDR circuit at the receiver for synchronization purposes.

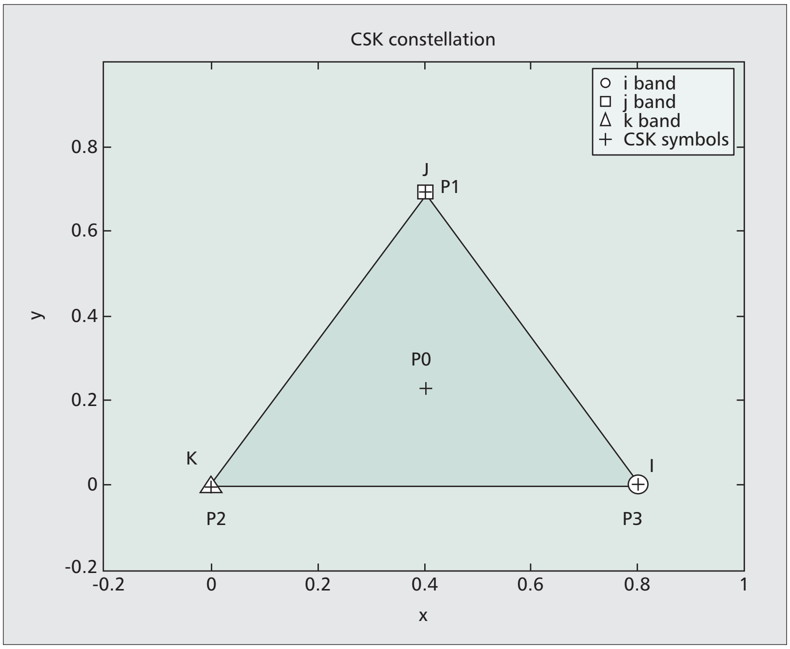

Figure 10. *Constellation design rule for 4-CSK. The x and y refer to chromaticity values. P1, P2 and P3 correspond to three points chosen from the seven wavelengths in the band plan. P0 is chosen to be the centroid of the triangle.*

- A simple approach should be used for visibility pattern generation. Designing 1000 patterns to support low resolutions (as low as 0.1 percent resolution) is not practical, and makes visibility pattern generation and use very complex.
- Since visibility patterns are transmitted without changing the clock frequency (in-band), avoid patterns that conflict with existing RLL code words.

A set of 11 base low resolution visibility patterns with 10 percent step size can be used for dimming. In fact, a set of 11 base low resolution visibility patterns of any length can be used as long as no conflict exists between the visibility pattern and a valid RLL code. Figure 15 provides such a set as an example. The low resolution patterns can be used to develop high resolution visibility patterns by averaging them across time to generate the required high resolution pattern. For example, if visibility patterns are available at 10 percent resolution, a 25 percent visibility pattern can be attained by alternately sending a 20 percent visibility pattern followed by a 30 percent visibility pattern. This method guarantees that all visibility patterns will retain the same properties as the base low resolution visibility patterns. The high resolution visibility pattern generation can be generalized by using the low resolution patterns according to the algorithm specified in the appendix. The high resolution dimming algorithm provides two patterns "*sel1pat*" and "*sel2pat*" out of the set of "$K+1$" available patterns with number of repetitions as "*reppat1*" and "*reppat2*" respectively. These two patterns are the closest available patterns on both sides of the precision requirement. For example, if visibility patterns are at 10 percent resolution, there are 11 patterns ($K = 10$), and any requirement between 20.01 and 29.99 percent will time-multiplex the 20 and 30 percent visibility patterns as shown in Fig. 15, and then adjust the repetition ratio of 20 and 30 percent patterns to get the required precision with the minimum number of repetitions.

Flicker Mitigation

The flicker in VLC is classified into two categories according to its generation mechanism: intra-frame flicker and inter-frame flicker. Intra-frame flicker is defined as the perceivable brightness fluctuation within a frame. Inter-frame flicker is defined as the perceivable brightness fluctuation between adjacent frame transmissions. This section outlines the methods used for flicker mitigation in VLC.

Intra-Frame Flicker Mitigation

Intra-frame flicker mitigation refers to mitigation flicker within the transmission of a data frame. Intra-frame flicker in OOK is avoided by using the dimmed OOK mode and RLL coding. VPPM uses RLL code and does not cause any inherent inter-frame flicker. Intra-frame flicker is avoided in CSK modulation by ensuring constant average power across multiple light sources along with scrambling and high optical clock rates (megahertz).

Inter-Frame Flicker Mitigation

Inter-frame flicker mitigation applies to both data transmission (RX mode) and idle periods. While idling, visibility patterns or idle patterns

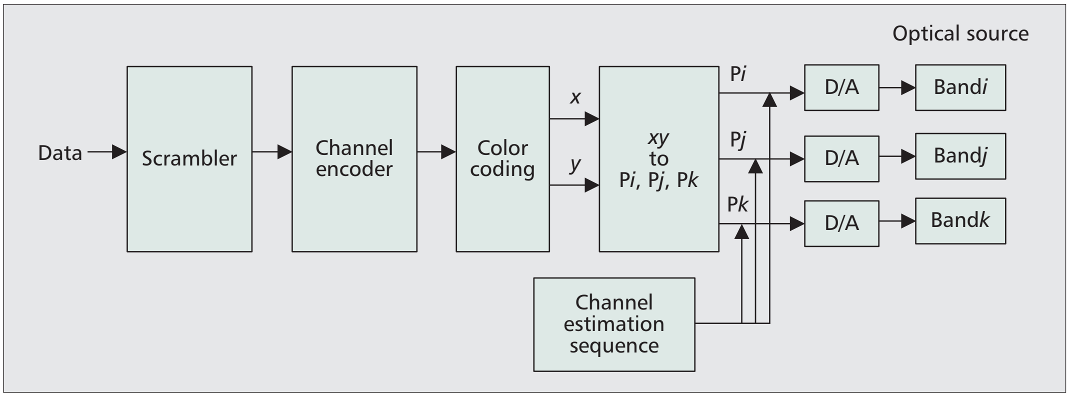

Figure 11. *CSK system diagram for PHY III. The data is scrambled to ensure randomness before encoding and mapping to intensity values which are then sent to three distinct wavelength optical sources.*

may be used to ensure light emission by the VLC transmitters have the same average brightness over adjacent MFTPs as during data transmission. These patterns can be modulated in-band or out-of-band (Fig. 14). When the dimmer setting is changed, the MAC and PHY layers adjust the data transmission and idle time transmission to fit the new dimmer settings. A summary of the different mitigation techniques for inter-frame and intra-frame flicker is provided in Table 5.

Conclusion

VLC provides the potential for multi-gigabit-per-second data rate communication at short distances with ~300 THz of available visible light spectrum at low power and cost, using simple LEDs and PDs. With the growing integration of LEDs in indoor and outdoor light sources, and advances in the design of low-cost LEDs with fast subnanosecond switching response times, the integration of lighting and communication provides significant potential for this technology. The two main challenges in communication in this spectrum are flicker mitigation and support for dimming. This article presents mechanisms to mitigate flicker and support dimming as defined in the IEEE 802.15.7 visible light communication standard.

Several technical challenges must be addressed to realize the full potential of VLC technology. First, channel models for VLC are not well understood, especially for outdoor non-line-of-sight (NLOS) environments, and there is an active area of research for channel models and platforms for VLC [13, 14]. Also, the networking of the light

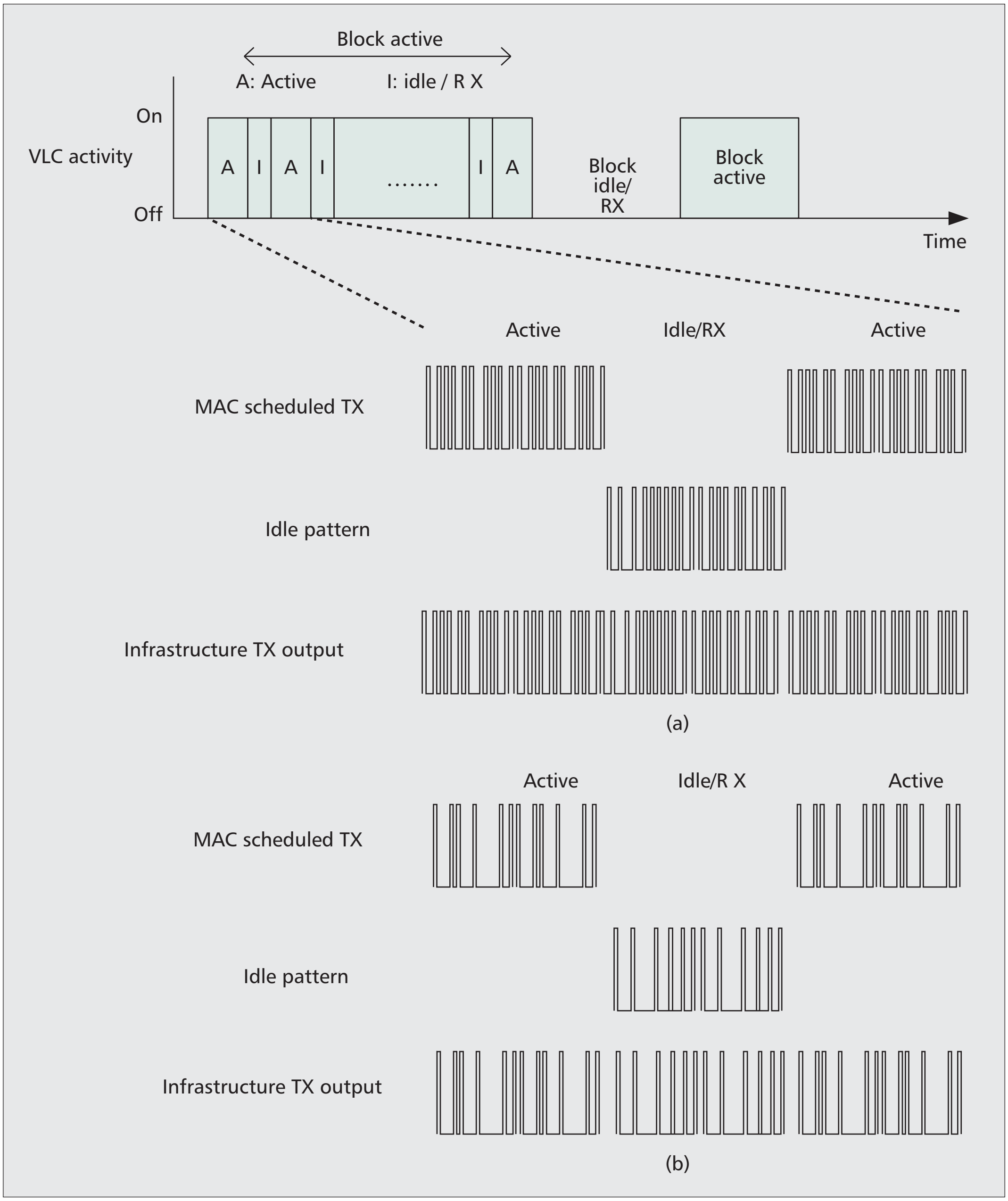

Figure 12. *Adapting dimmer pattern and data duty cycle based on dimmer setting using the MAC knowledge of active and idle states and keeping a constant duty cycle to mitigate flicker.*

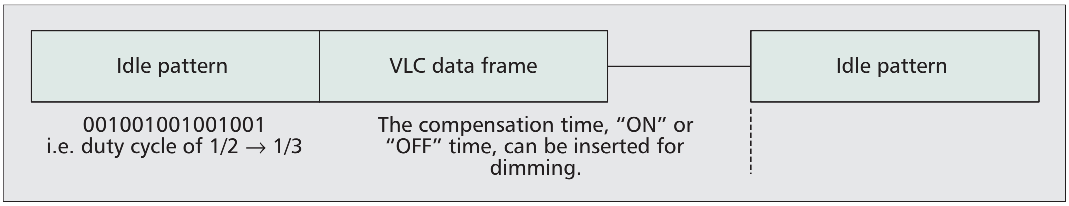

Figure 13. *Idle pattern and compensation time dimming where the compensation time and idle times are inserted during data transmission with appropriate duration to mitigate flicker.*

sources and upgrading current infrastructures to support communication is another challenge, which requires support from the lighting industry. With continued growth in LED based light sources and the need for multi-Gb/s data distribution, VLC, being developed as a global industry standard in IEEE 802.15.7, promises to be a very attractive candidate as a future high data rate and power-efficient technology.

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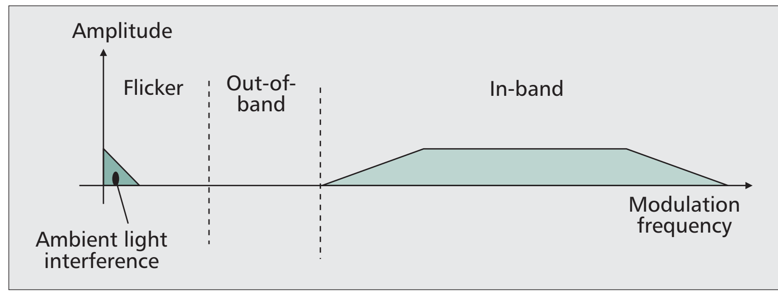

Figure 14. *Modulation domain spectrum for visible light communication. The use of flicker mitigation schemes ensure that there is no data transmitted in the lower frequencies, where flicker occurs.*

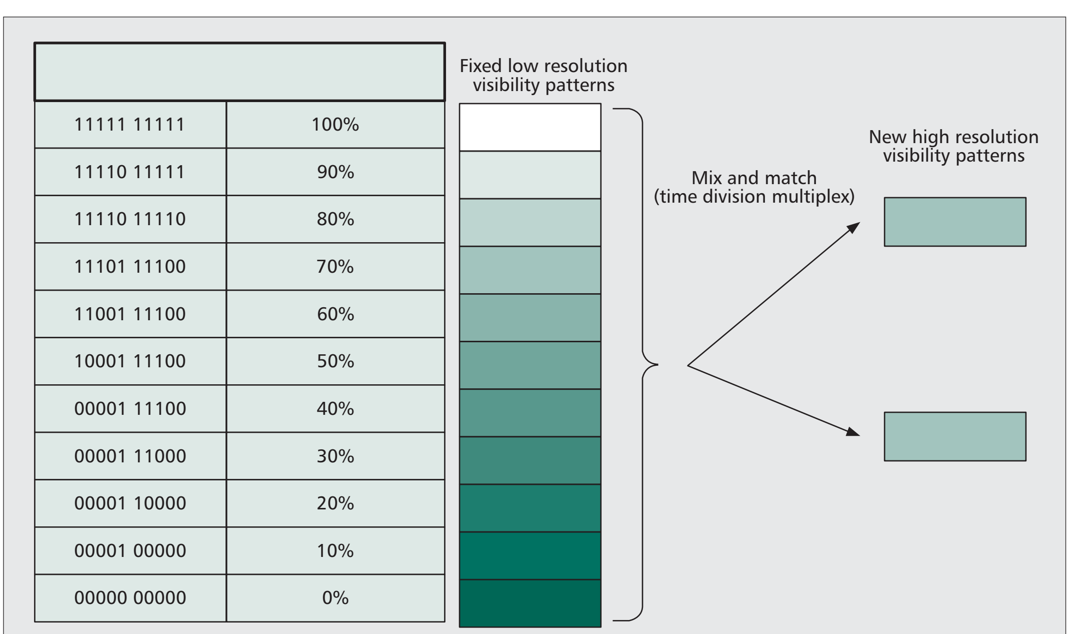

Figure 15. *High resolution dimming with visibility patterns. High resolution visibility patterns are generated by time-division multiplexing low resolution visibility patterns.*

Flicker mitigation	Data transmission (Intra-frame flicker)	Idle or RX periods (Inter-frame flicker)
OOK modulation	Dimmed OOK mode, RLL code	
VPPM modulation	VPPM guarantees no intra-frame flicker, RLL code	Idle/visibility patterns
CSK modulation	Constant average power across multiple light sources, scrambler, high optical clock rates (MHz)	

Table 5. *Flicker mitigation schemes.*

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Appendix

Algorithm for high resolution dimming:

Let the following values be defined as

- 'K+1' Visibility patterns: $V_0, V_1, \ldots, V_K$
- Desired visibility = dv (expressed as a percentage value) e.g., for a 25.3 percent visibility, dv = 25.3
- Desired precision = p, $p \leq 0$, p is an integer (expressed as a logarithm value) e.g., for 0.01 percent, precision, p = –2

Then define the selected patterns as *sel1pat* and *sel2pat*.

$$\text{sel1pat} = \left\lfloor \frac{dv * 10^{-p}}{K} \right\rfloor \tag{6}$$

$$\text{sel2pat} = \left\lceil \frac{dv * 10^{-p}}{K} \right\rceil \tag{7}$$

The number of repetitions of the selected patterns is given as *reppat1* and *reppat2*. The number of repetitions for these patterns can be selected as follows.

$$\text{reppat2} = 10^{-p}\left(dv - \frac{100 * sel1pat}{K}\right) \tag{8}$$

$$\text{reppat2} = 10^{1-p} - reppat2 \tag{9}$$

Then, to achieve visibility dv:
–repeat V_{sel1pat} *reppat1* times, and
–repeat V_{sel2pat} *reppat2* times.

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